

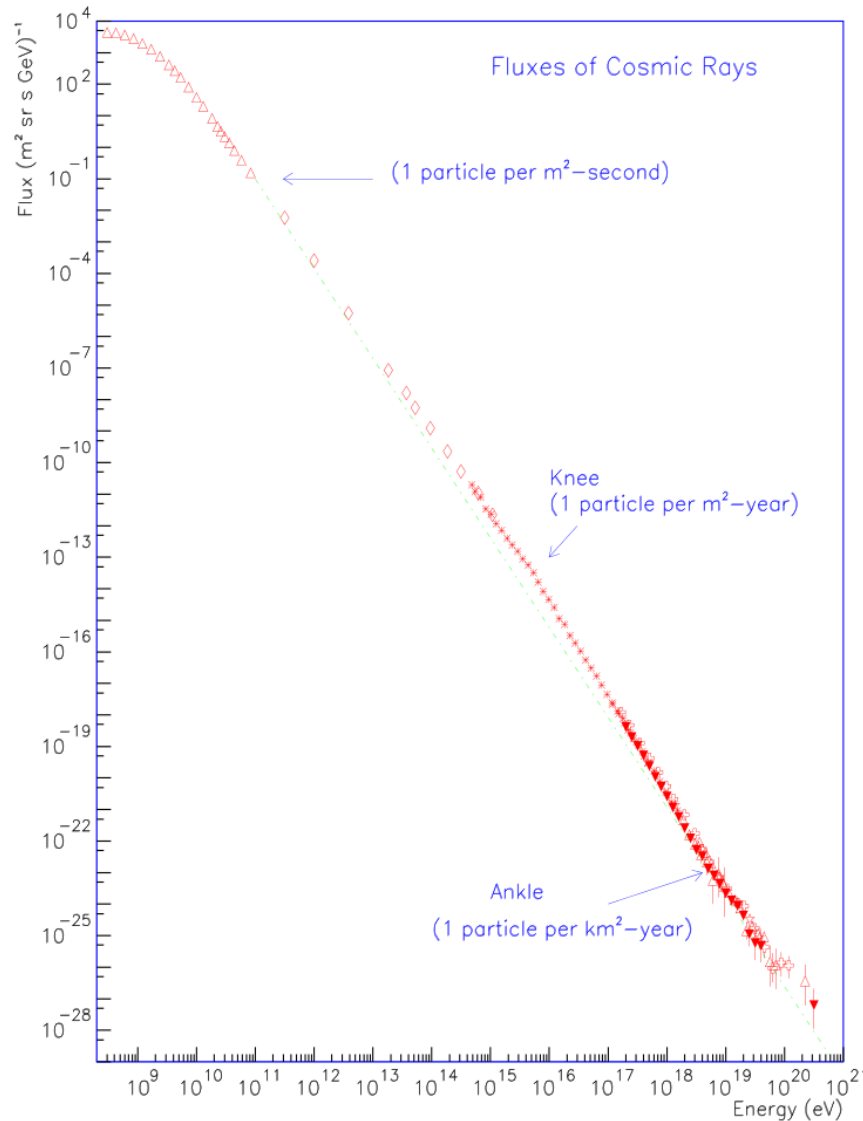
**PIERRE  
AUGER**  
OBSERVATORY

# The Pierre Auger Observatory: Cosmic Rays at the Highest Energies

Jeff Allen (New York University)

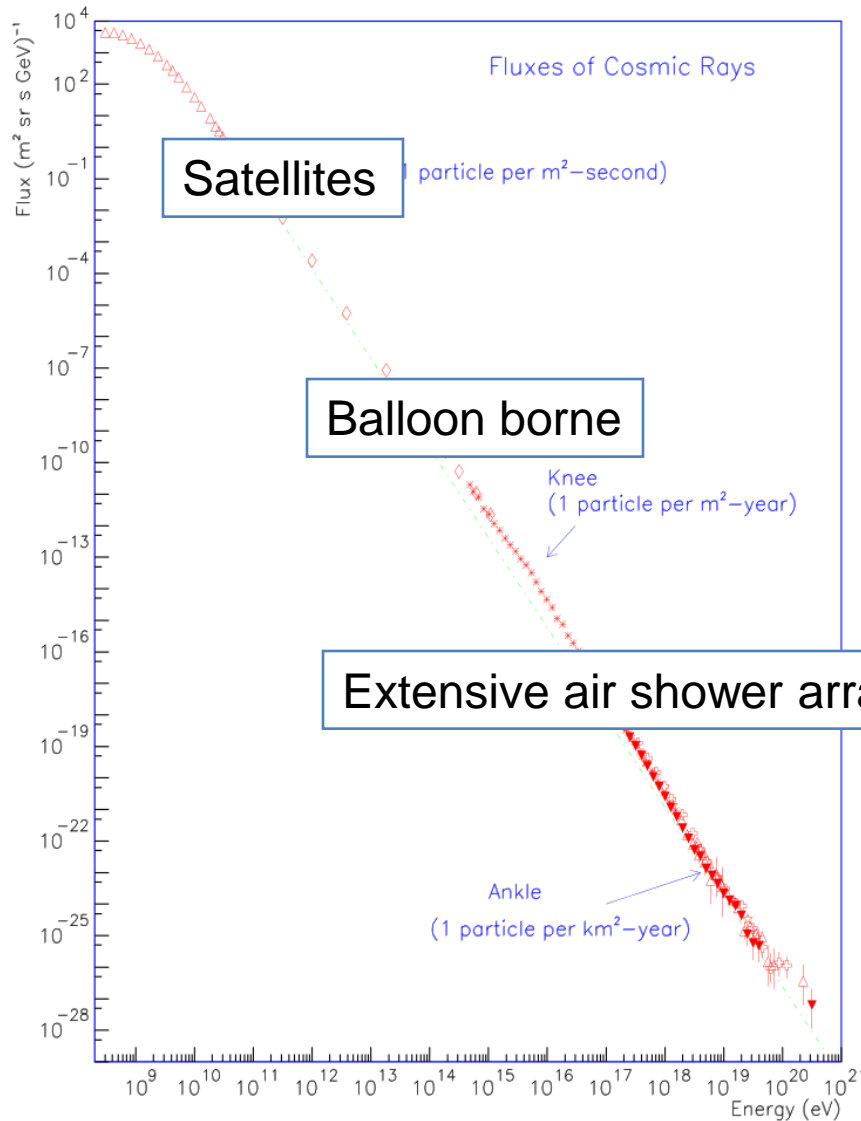
For the Pierre Auger Collaboration

# Cosmic Rays



- Fairly constant power law spectrum over 10 decades in energy
- Extremely low flux at the highest energies,  $\sim 1$  per  $\text{km}^2$  per century
- Open questions
  - Galactic to extra-galactic transition
  - Sources
  - Composition

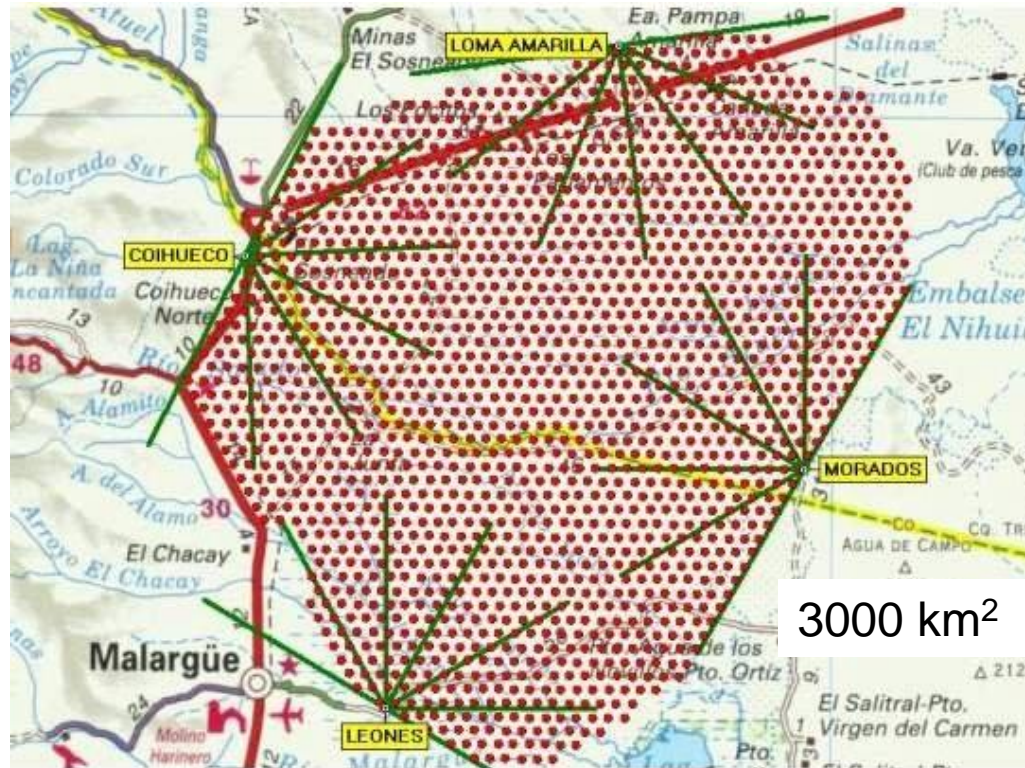
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# The Pierre Auger Observatory

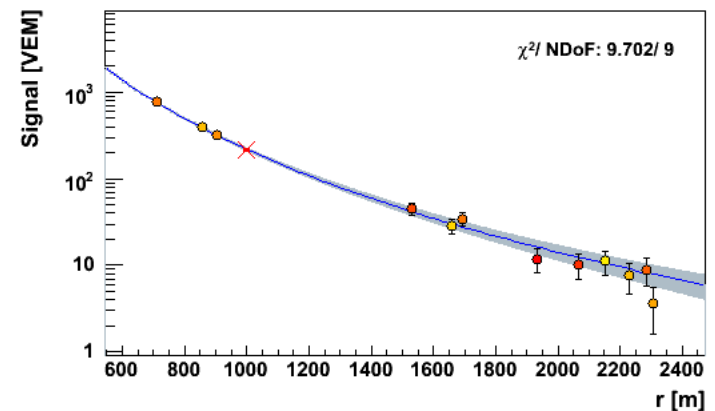
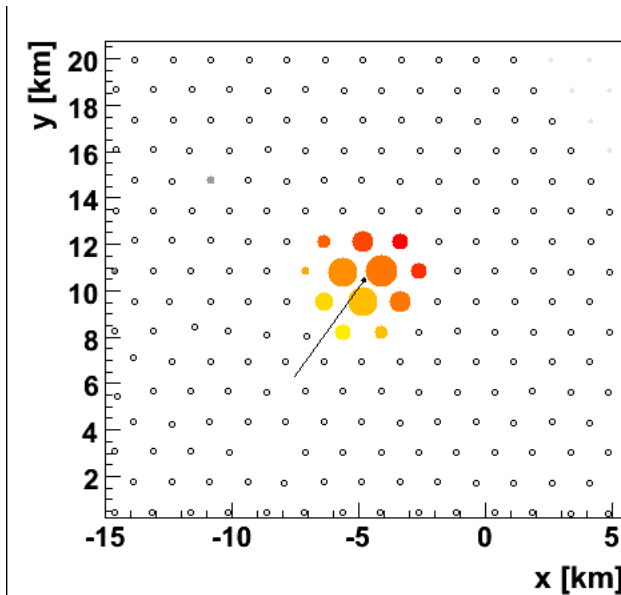
- Largest detector in operation
- 490 scientists from 18 countries



Argentina, Australia, Bolivia, Brazil, Croatia, the Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, the United Kingdom, the United States, and Vietnam.

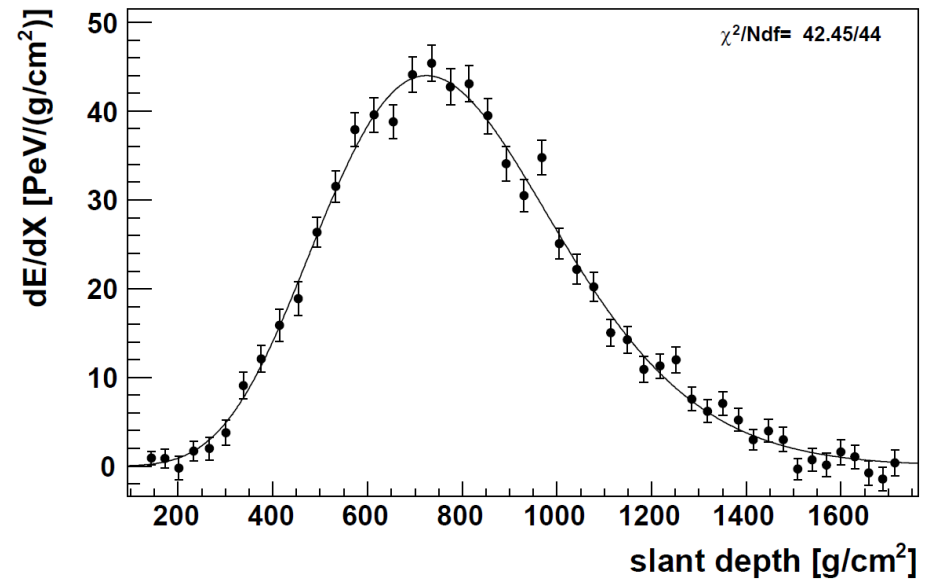
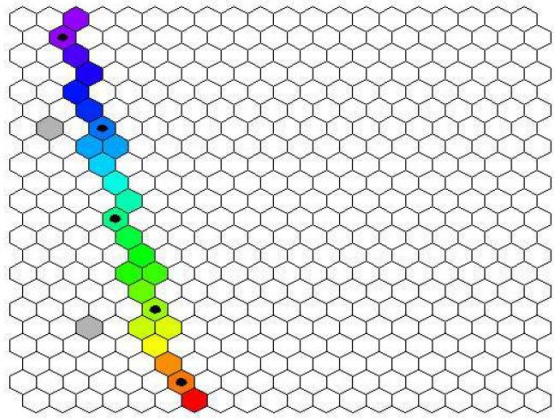
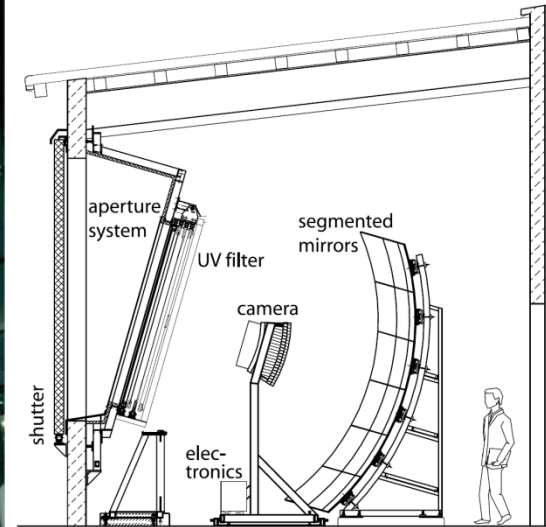
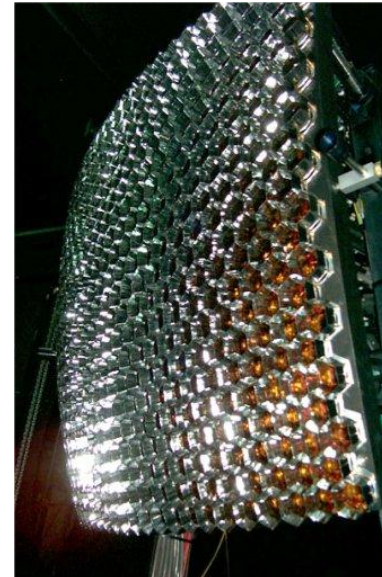
# Surface Array (SD)

- High energy air showers leave large footprint on the ground
- 1600 water Cherenkov tanks with 1.5 km spacing
  - Each detector self calibrates and triggers
- Fully efficient around 3 EeV
- Angular reconstruction from GPS timing
  - $< 1^\circ$  at high energies



# Fluorescence Telescopes (FD)

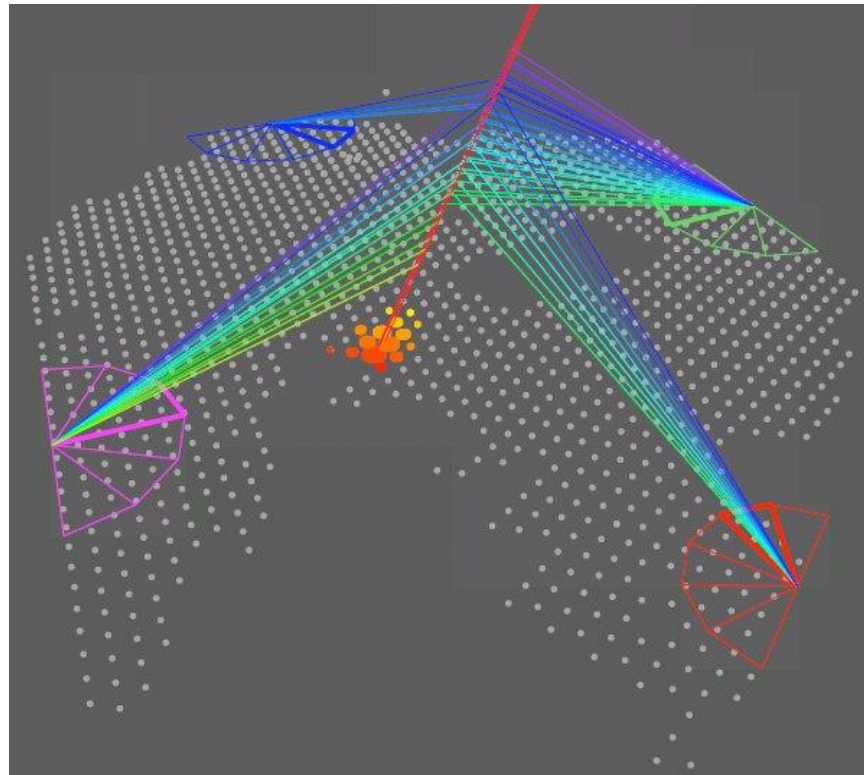
- Charged particles ionize the atmosphere
- Resulting fluorescence light viewed by 24 telescopes at four sites
- Provides nearly calorimetric energy reconstruction





# Hybrid Detector

- Hybrid technique makes Auger truly unique
- Air showers detected with both techniques are some of the best constrained showers detected



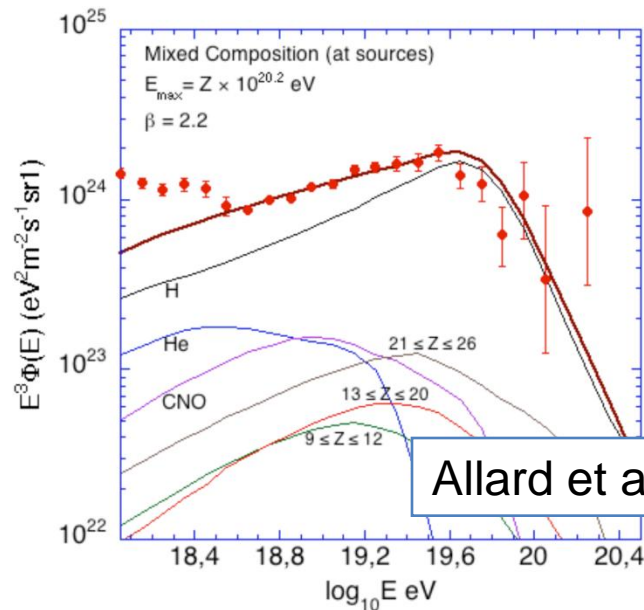
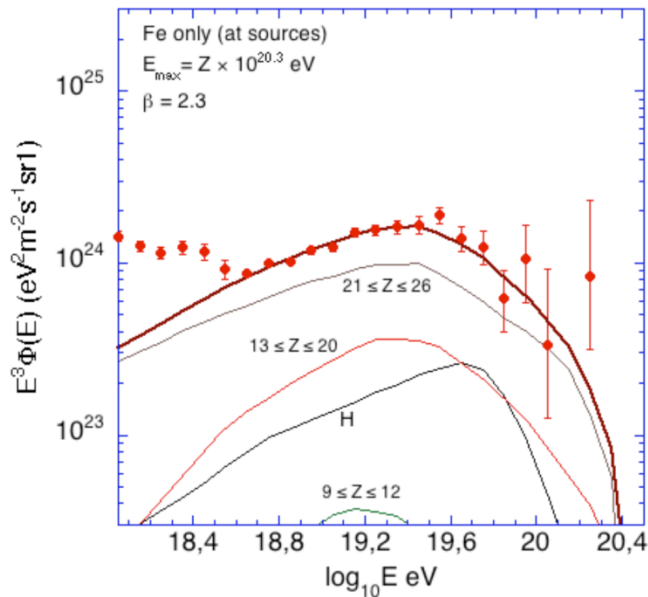
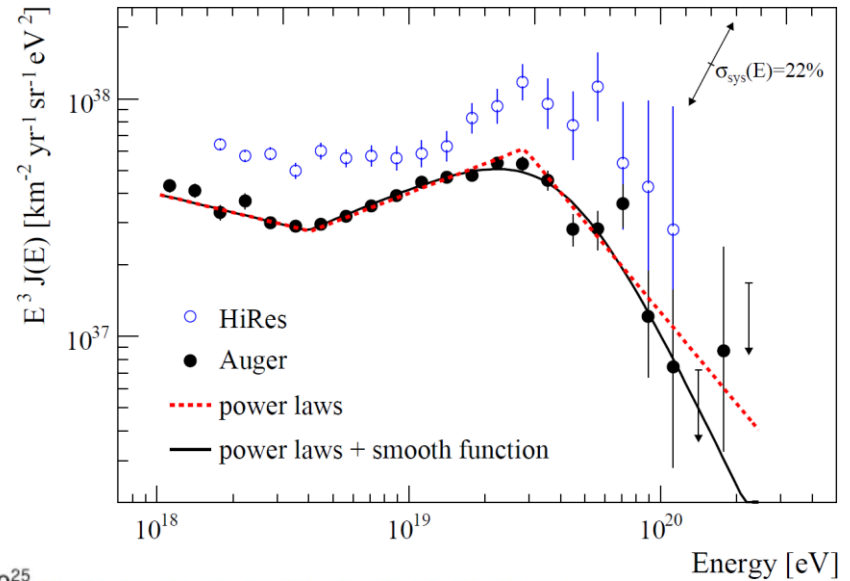
# Science Goals

- Measure the flux of UHECR ( $E > 1\text{EeV}$ )
- Determine sources and nature of acceleration
  - Correlation seen in the arrival directions with AGN within 70 Mpc
- Study composition of UHECR
  - Proton, iron, intermediate?
- Look for air showers generated by all types of particles
  - Photons
  - Neutrinos
  - Exotics?



# Energy Spectrum

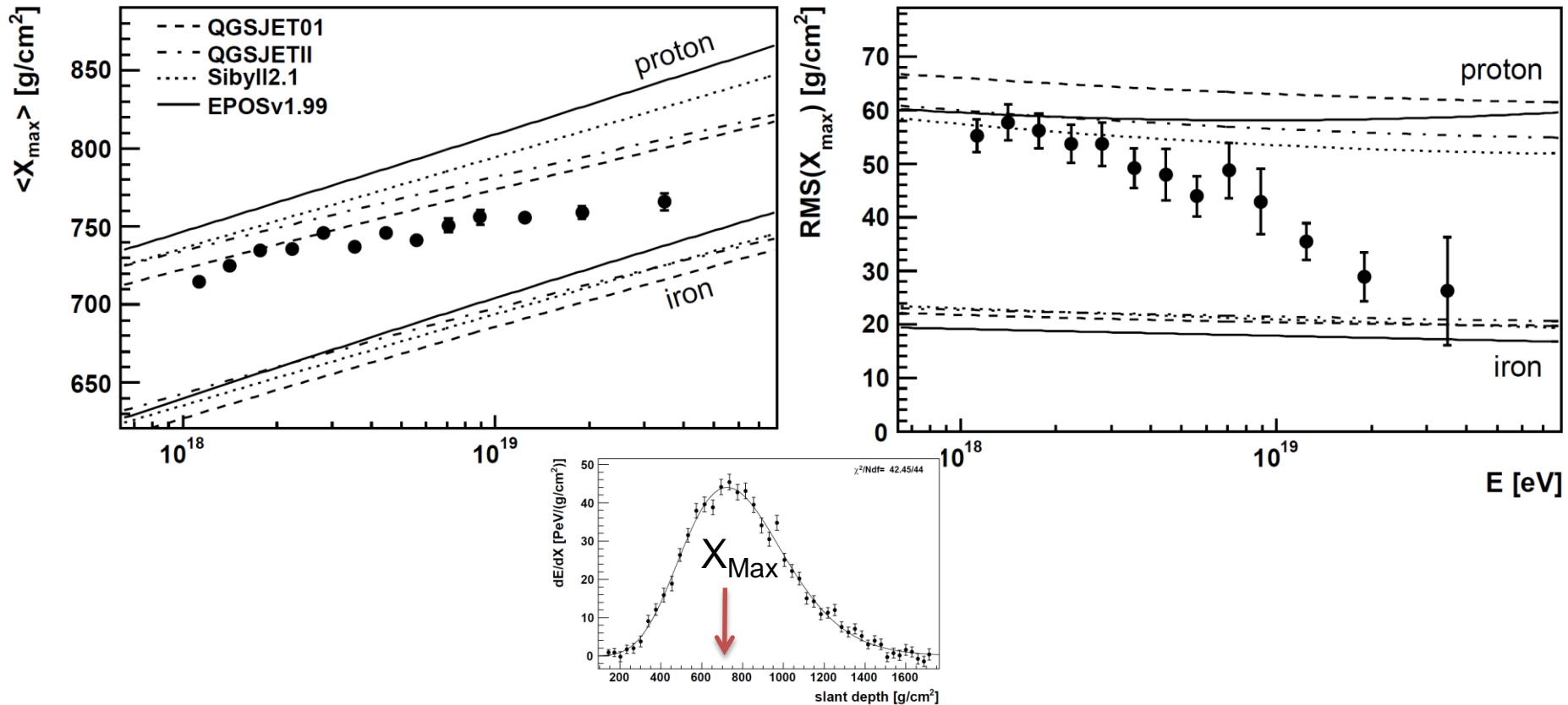
- Ankle seen at 4 EeV
  - Possible location of galactic to extra-galactic transition
- High energy cutoff seen above 30 EeV
  - Spectral index drops to -4.3
  - GZK? Photodisintegration?
- Current energy spectrum can be fit by iron or proton



Allard et al 2008

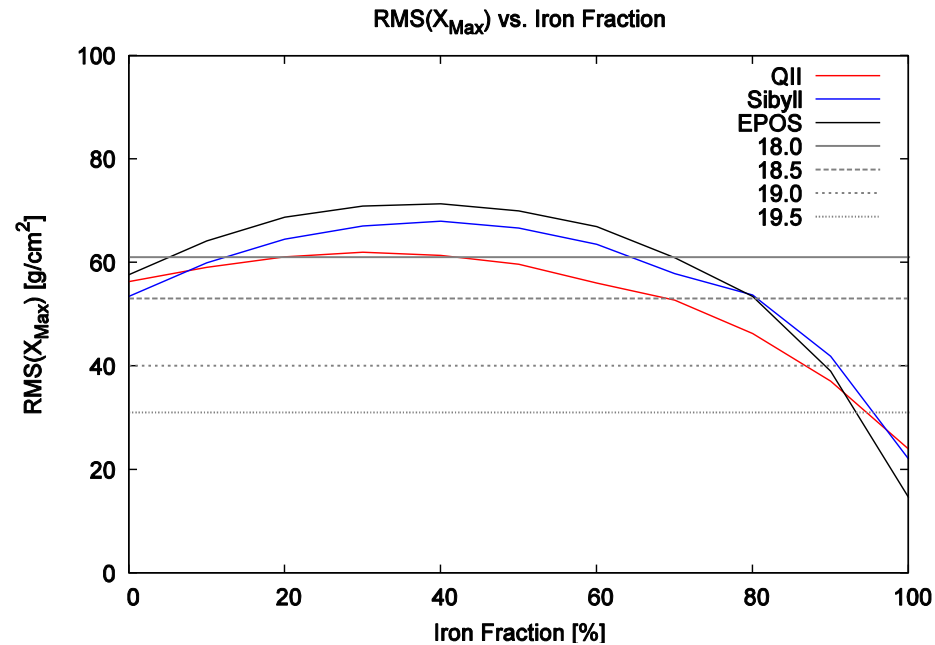
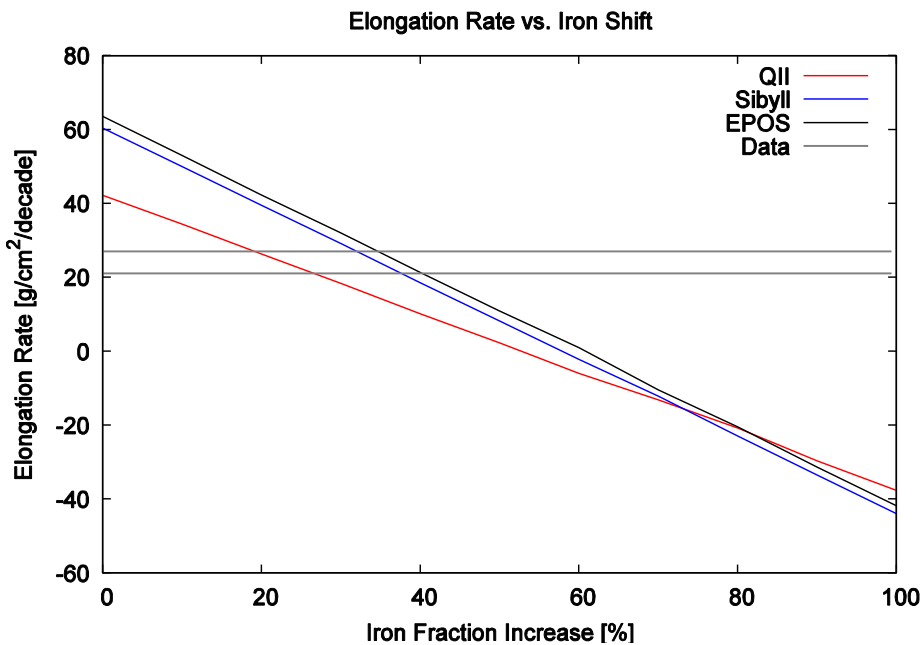
# $X_{\text{Max}}$ : Composition

- Depth of shower maximum ( $X_{\text{Max}}$ ) sensitive to the composition
  - Both mean and variance are useful tools in determining the mass and evolution
- Current results point to increasingly heavy mass, from MC simulations



# $X_{\text{Max}}$ : Comparison to Models

- Quantitative interpretation is possible with the use of MC simulations and models of the high-energy interactions
  - Rely on extrapolations from accelerator data (Take with grain of salt)
- Taking MC predictions at face value, results consistent within measurement and theoretical uncertainty

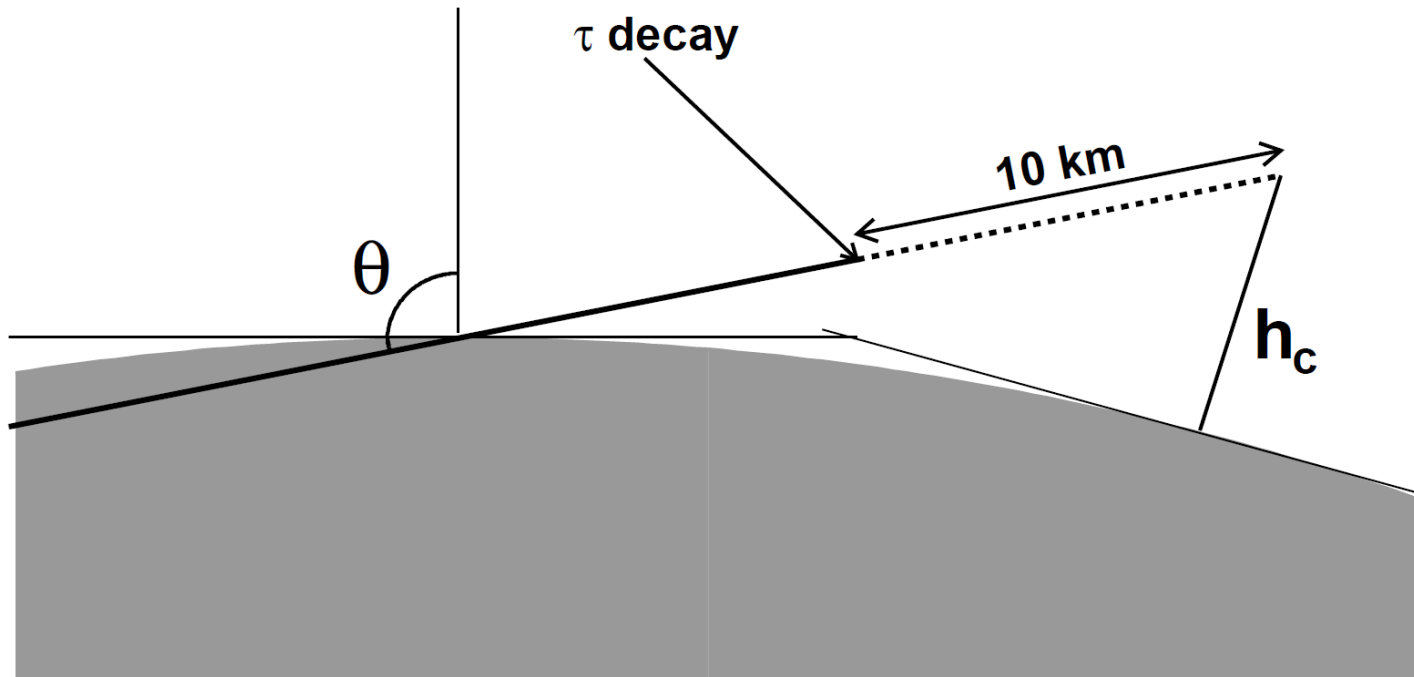


# Beyond Cosmic Rays

- Auger detects air showers.
  - Can be initiated by photons, neutrinos, or even exotic particles!

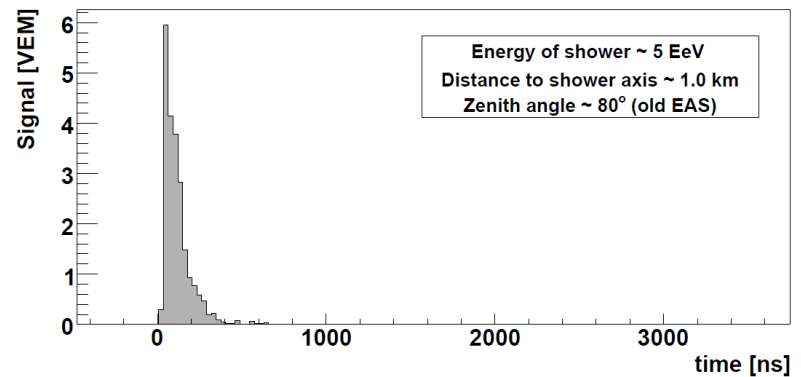
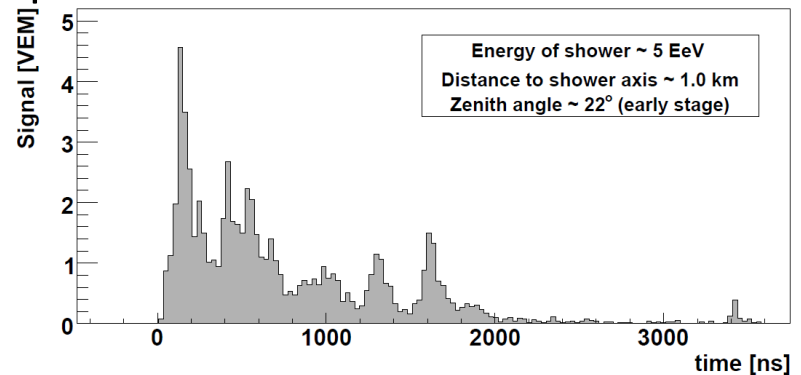
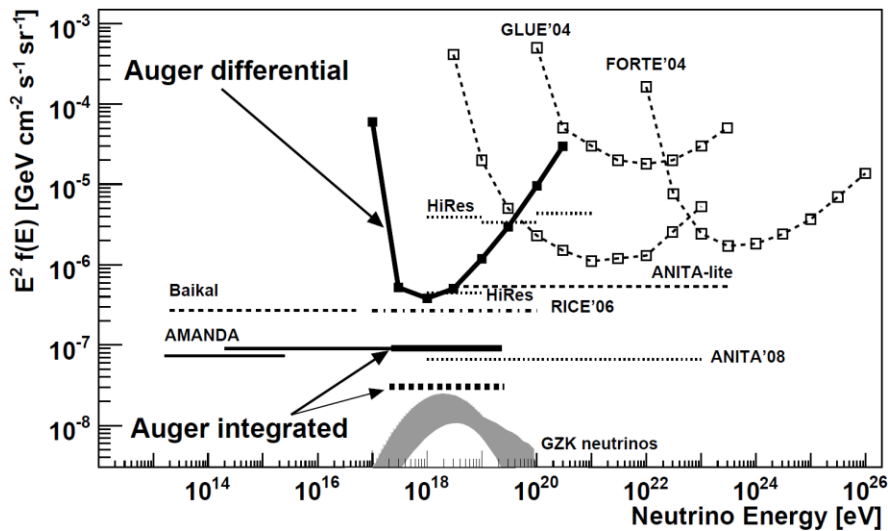
# Neutrinos

- Large target mass provided by the earth
  - “Earth Skimming” tau-neutrinos can interact near the surface of the earth
  - Decaying tau initiates an EM rich shower at nearly horizontal showers



# Neutrinos

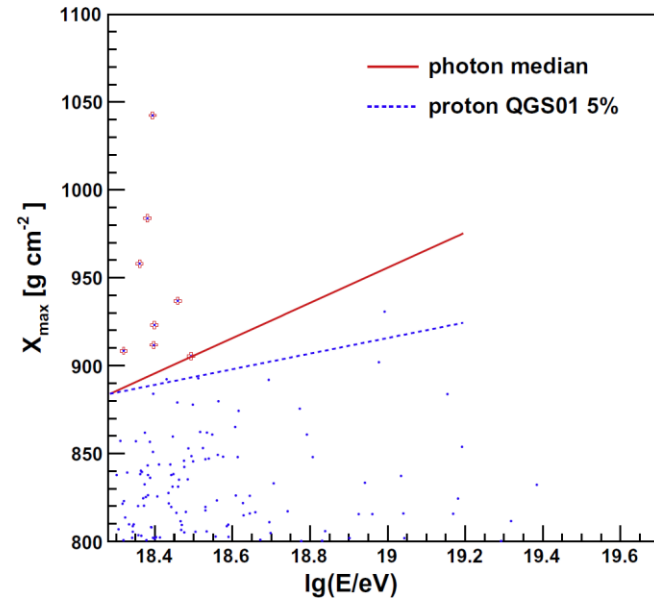
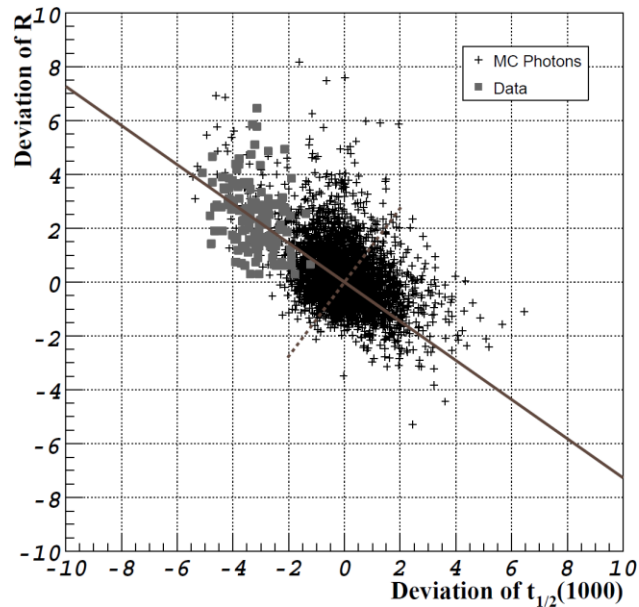
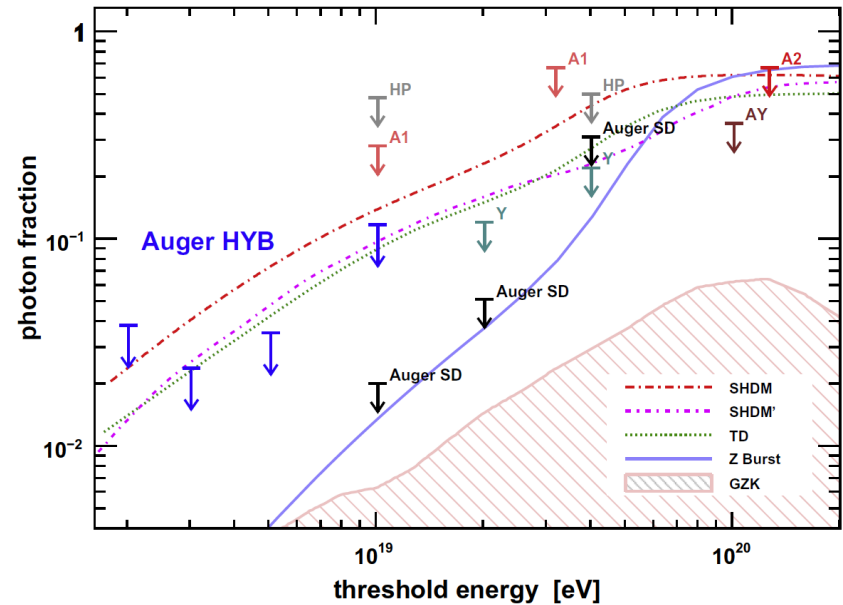
- Decaying tau initiates an EM rich shower at nearly horizontal angles
  - EM component can be detected through the FADC trace of surface detectors
- Horizontal showers will produce elongated footprints
  - Time difference between neighboring tanks  $\sim$ light travel time
- No candidates observed, but limit is competitive in the field





# Photons

- Photons can be seen in SD as muon poor showers
- Can be seen in FD as showers with deep  $X_{\text{Max}}$
- Separation not perfect in either case
  - Candidates exist
  - Limits the photon fraction
- Current limit rules out some exotic models of UHECR creation



# Conclusion

- Construction of Auger completed in 2008, but work not done
  - AMIGA and HEAT are low energy extensions, take Auger down to the second knee
  - Radio R&D could provide a FD type detector with ~100% duty cycle
- Composition of cosmic rays
  - Taking models at face value, suggests mixed composition around 1 EeV transitioning to heavier elements
- Large air shower observatories are useful beyond cosmic rays
  - Neutrino limits competitive with dedicated neutrino experiments
  - Photon limits can rule out several “exotic” models of UHECR creation